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Smart Battery Controller for Lithium Sulfur Dioxide Batteries

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August 1992

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Each year, the U.S. Army purchases millions of lithium sulfur dioxide batteries for use in portable electronics equipment. Because of their superior rate capability and service life over a wide variety of conditions, lithium batteries are the power source of choice for military equipment. There is no convenient method of determining the available energy remaining in partially used lithium batteries; hence, users do not take full advantage of all the available battery energy. Currently, users replace batteries before each mission, which leads to premature disposal, and results in the waste of millions of dollars in battery energy every year. Another problem of the lithium battery is that it is necessary to ensure complete discharge of the cells when the useful life of the battery has been expended, or when a hazardous condition exists; a hazardous condition may result in one or more of the cells venting. The Electronics Technology and Devices Laboratory has developed a working prototype of a smart battery controller (SBC) that addresses these problems.

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INTRODUCTION

Each year the U.S. Army purchases millions of lithium sulfur dioxide batteries for use in portable electronics equipment. Because of their superior rate capability and service life over a wide variety of conditions, lithium batteries are the power source of choice for military equipment.

There is no convenient method of determining the available energy remaining in partially used lithium batteries; hence, users do not take full advantage of all the available battery energy. Currently, users replace batteries before each mission, which leads to premature disposal, and results in the waste of millions of dollars in battery energy every year.

Another problem of the lithium battery is that it is necessary to ensure complete discharge of the cells when the useful life of the battery has been expended, or when a hazardous condition exists; a hazardous condition may result in one or more of the cells venting. The Electronics Technology and Devices Laboratory (ETDL) has developed a working prototype of a smart battery controller (SBC) that addresses these problems.

SYSTEM REQUIREMENTS

The following are the SBC requirements:

a. monitor battery usage, this includes external temperature of each cell and the current drain.

b. display to the user the percentage of remaining energy in the battery.

c. determine if a hazardous condition exists within the battery;

d. perform a complete discharge of the battery when the hazardous condition exists, or when the user determines that the battery's useful life has been met;

e. fit into the available volume of existing battery packages, consume negligible power, be low cost;

SYSTEM OVERVIEW

The SBC is designed for incorporation into the BA-5590/U battery, which consists of 10 D-sized cells arranged in two sets of five in series. Each cell produces 3.0 volts nominal and is capable of greater than 10 amps of peak current. Figure 1 is a block diagram of the system, which consists of three major components: a microcontroller and two application-specific integrated circuits (ASICs).

There is one ASIC for each string of five cells. Each ASIC is responsible for providing information to the microcontroller about: 1) the voltage across each of its five cells, 2) fuse continuity, 3) external temperature of each cell, and 4) the string's current drain. One of the ASICs is wired directly to the microcontroller; the other is connected to the microcontroller via optical couplers. Only the ASIC that is wired directly to the processor provides temperature information. The ASIC and microcontroller are designed to be used with other types of lithium sulfur dioxide cells. Figure 2 is a block diagram of the ASIC.

HARDWARE DESCRIPTION (ASIC)

Power Up

In order to conserve battery power and minimize the drain that the SBC circuits have on the battery during storage, only a small portion of the SBC system remains powered up after production. When the battery is to be used, a plug is removed from the battery connector, which powers up the remaining portions of the SBC. Once activated, the system is "on" permanently.

Voltage and Fuse Monitoring (comparator circuit)

The SBC evaluates the voltages across the individual cells and the state of both the fuse and thermal switch. The battery is considered beyond its useful life if any cell is below 1.5 volts. When this condition occurs, the SBC electronically disconnects the battery from the load and initiates the cell discharge mechanism.

The battery is also considered beyond its useful life if the fuse or thermal switch is open. The SBC monitors the thermal switch and fuse by examining the voltage drop across the resistor that is placed across the fuse and thermal switch. A drop of greater than 1.5 volts across this resistor indicates that the fuse is blown. The SBC will then electronically disconnect the battery from the load and initiate the cell discharge mechanism.

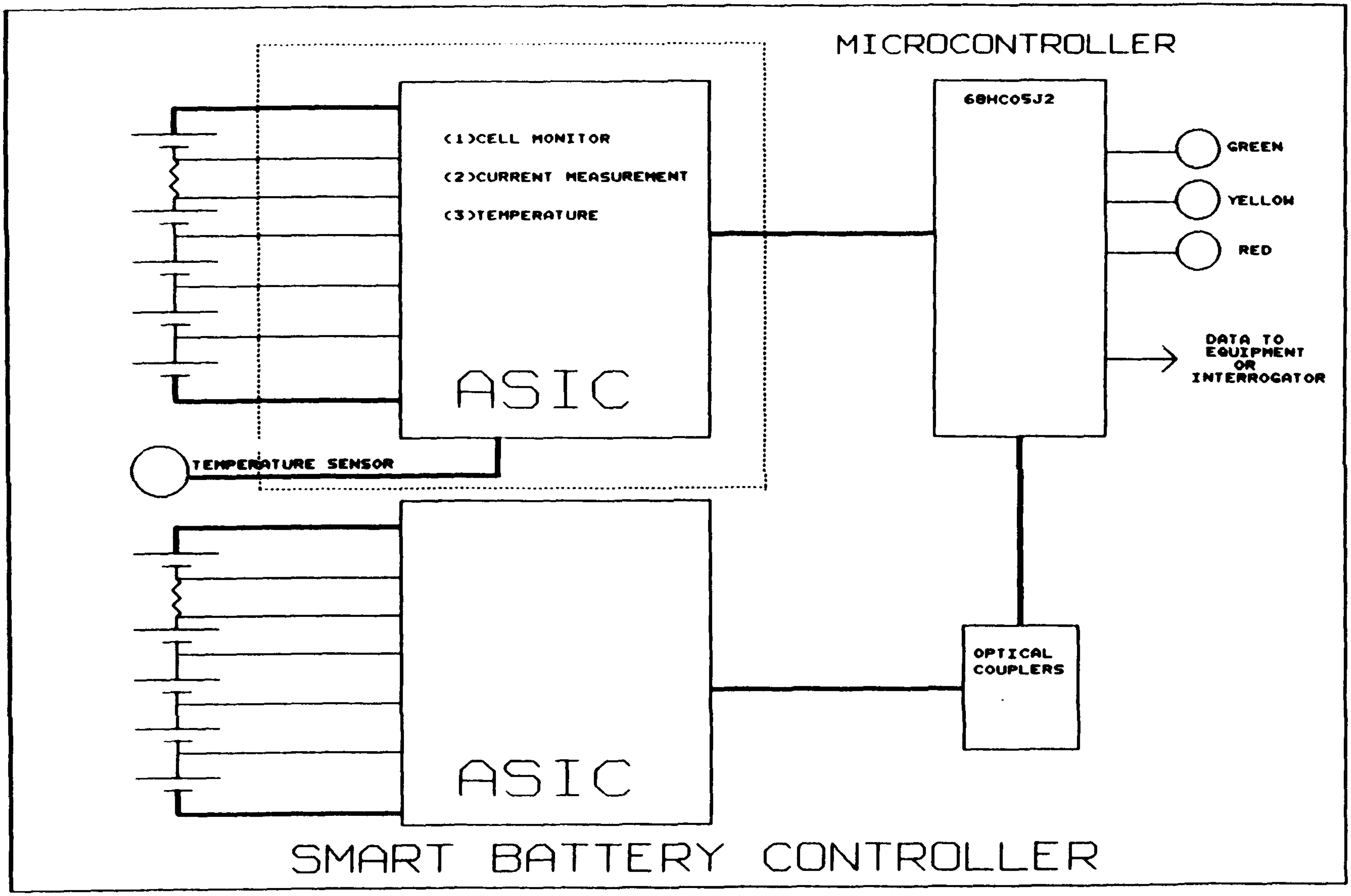

FIGURE 1. Block Diagram of 'Smart' Battery Controller

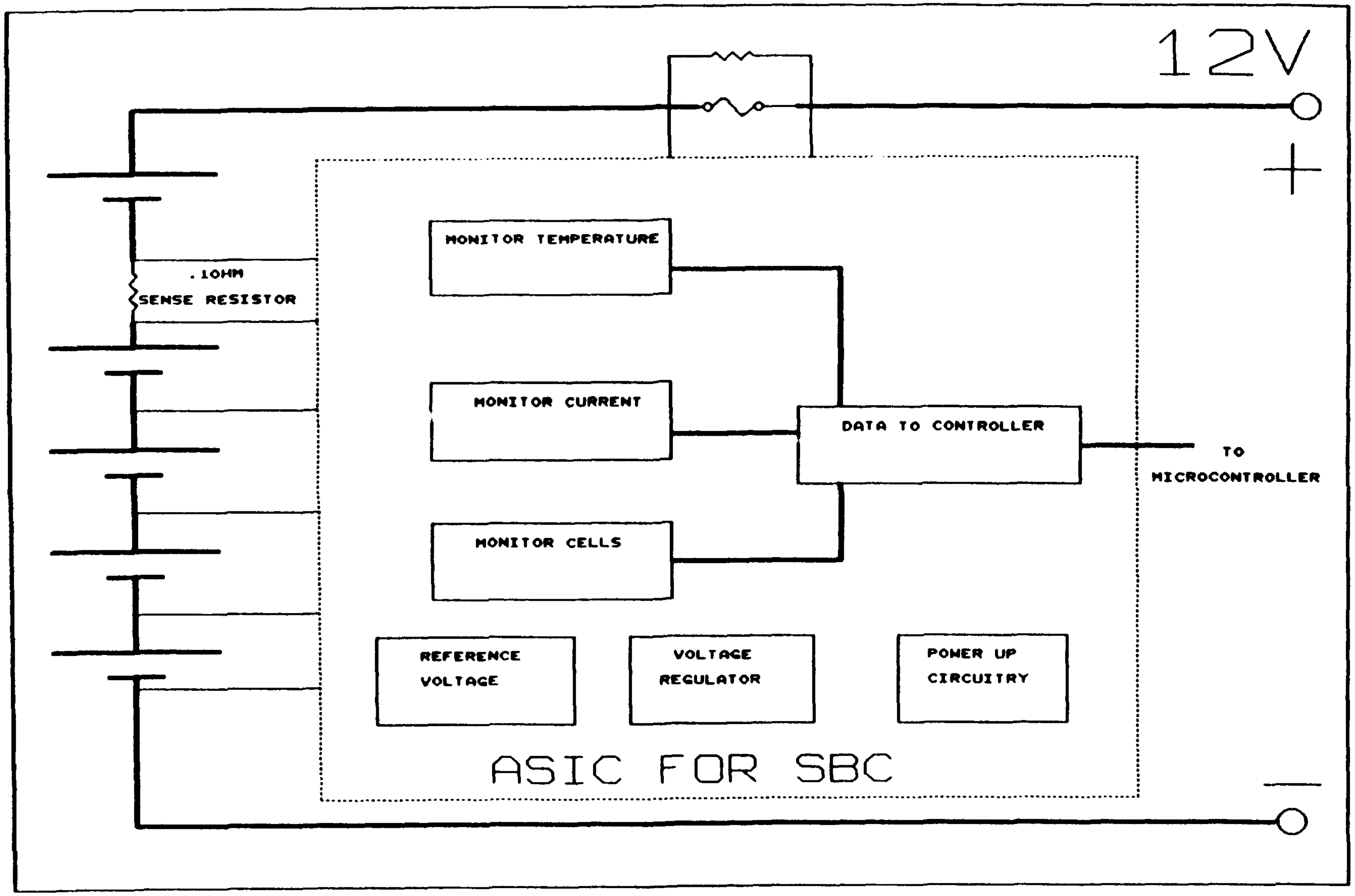

FIGURE 2. Block Diagram of 'Smart' Battery Controller ASIC

Cell Discharge

The discharging of the cells is accomplished by grounding the junction point between the fuse and protection diode. When this occurs, the fuse is blown, and all the remaining energy is depleted from the cells through the discharge resistor. The mechanism that grounds the junction point must remain in the "on" position until the battery cells are discharged to a safe state.

Reference Voltage

This small circuit block provides a stable reference voltage over temperature for use in the comparator circuits noted previously and in the current monitoring circuit.

Current Monitoring

For the SBC to monitor the battery's current drain, a 0.1 ohm sense resistor is placed between two cells. The voltage drop across this sense resistor is integrated by utilizing an operational amplifier. The output of the integrator is compared to a reference voltage and is used to control a binary counter. The ASIC generates an interrupt after the reference voltage is reached, and it shifts the 16-bit binary count to the processor. This binary count is a function of the amount of current depleted from the battery during that integration interval. No interrupts are generated if less than 37 milliamps are being drawn from the string cells.

Temperature Sensor

A thermistor is embedded within the group of battery cells; its current output is used to charge a capacitor. The processor determines the amount of time the capacitor takes to charge from its discharged state to the reference voltage; this produces a count which is a function of temperature. Temperature data is quantized into 20 ranges. The temperature measurements are critical to the accurate computation of energy depleted from the battery.

HARDWARE DESCRIPTION (PROCESSOR)

The SBC uses a Motorola 8-bit, low-power, low-cost micro-controller that was chosen for this application because of its mix of built-in support (RAM, ROM, countertimers), low cost, and power consumption. When active, the controller is clocked at approximately 32 kHz. It provides the functional control of the modules discussed previously, and it performs the computa-

tions that are necessary to derive the status information required. This information is displayed through the I/O ports discussed later.

Input and Output

The input to start up the system is implemented with a storage plug. Once the storage plug is removed, the system is activated permanently. The other mechanism input to the battery is a momentary switch, which is depressed when the user wants a visual indication of the condition of the battery. Upon sensing the pressing of the button, the SBC will activate three LEDs.

The LEDs are three different colors (green, yellow, red) and are used to indicate to the user the relative remaining lifetime of the battery. Currently, the green LEDs represent greater than 64 percent, the yellow LED between 32 and 65 percent, and the red LED a value below 33 percent. At present, the threshold is 32 percent, but this may be modified, based on future system testing. Multiple LEDs were used instead of a simple "go/no-go" display to eliminate faulty interpretation due to a single point LED failure.

If the battery level is below a minimal operating level, and if the button requesting battery data continues to be depressed for a 16-second period, the operator will be alerted that the battery is rendered safe (power totally drained).

In addition to the LEDs, the system also sends out a bit stream of data on the center pin of the battery connector. The communications protocol and an instrument which receives and displays this data have also been developed by ETDL; the data consists of a binary number that represents the percentage of the battery's remaining energy. Figure 3 is a timing diagram depicting the communications protocol.

Interrogator Description

The serial data is intended for use by equipment that is capable of reading it: a handheld battery instrument, or a handheld battery interrogator. Figure 4 is a block diagram of the interrogator connected to the SBC. It consists of a level translator, microcontroller, and two seven-segment displays.

Level Translator

The operating voltage of the equipment's electronics may be different than the voltage of the battery. This requires a shift in the voltage levels of the data. Because the output of the SBC is of the open-drain type, the interrogating equipment can adjust the voltage swings of the data.

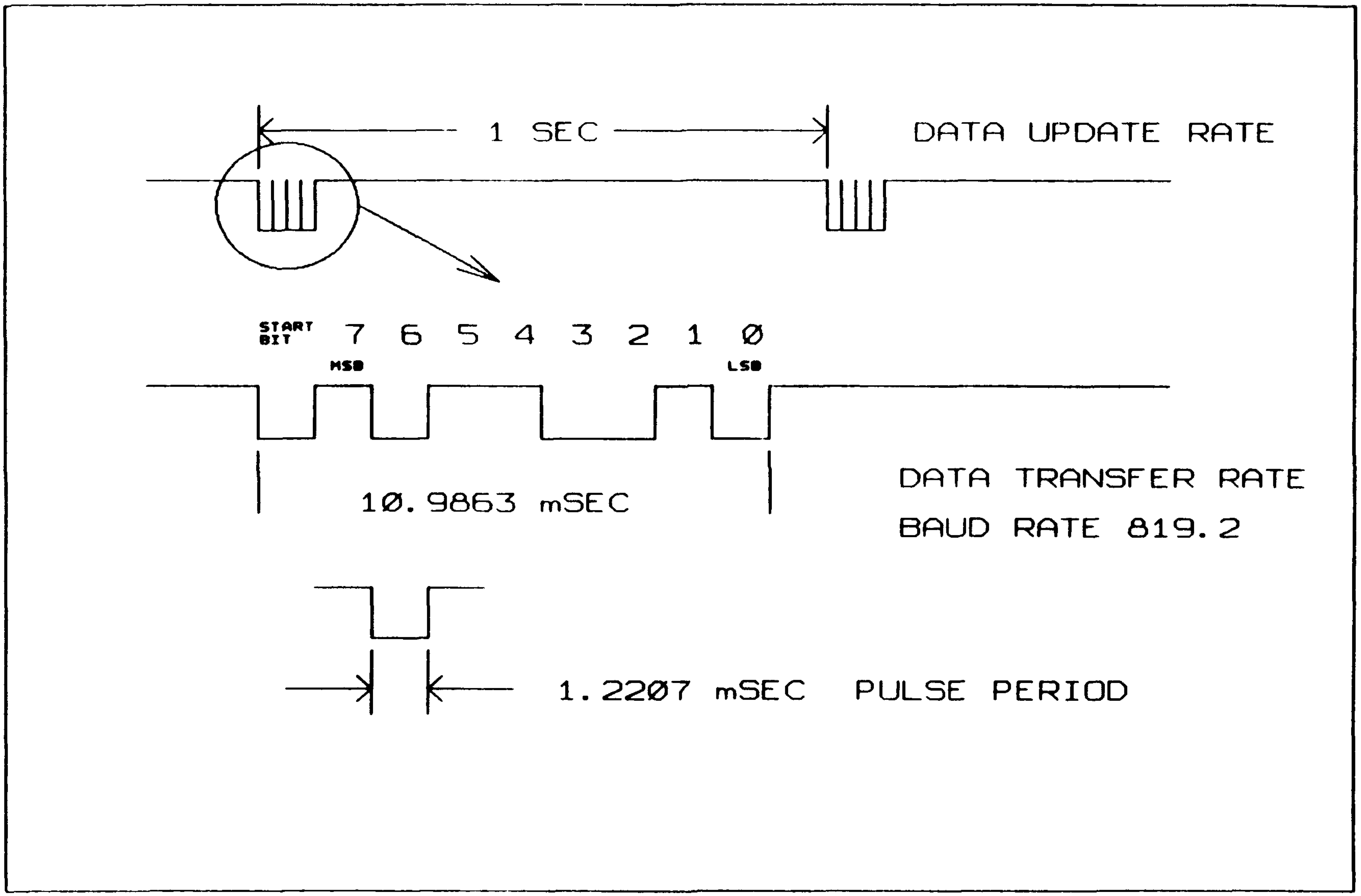

FIGURE 3. Data output protocol

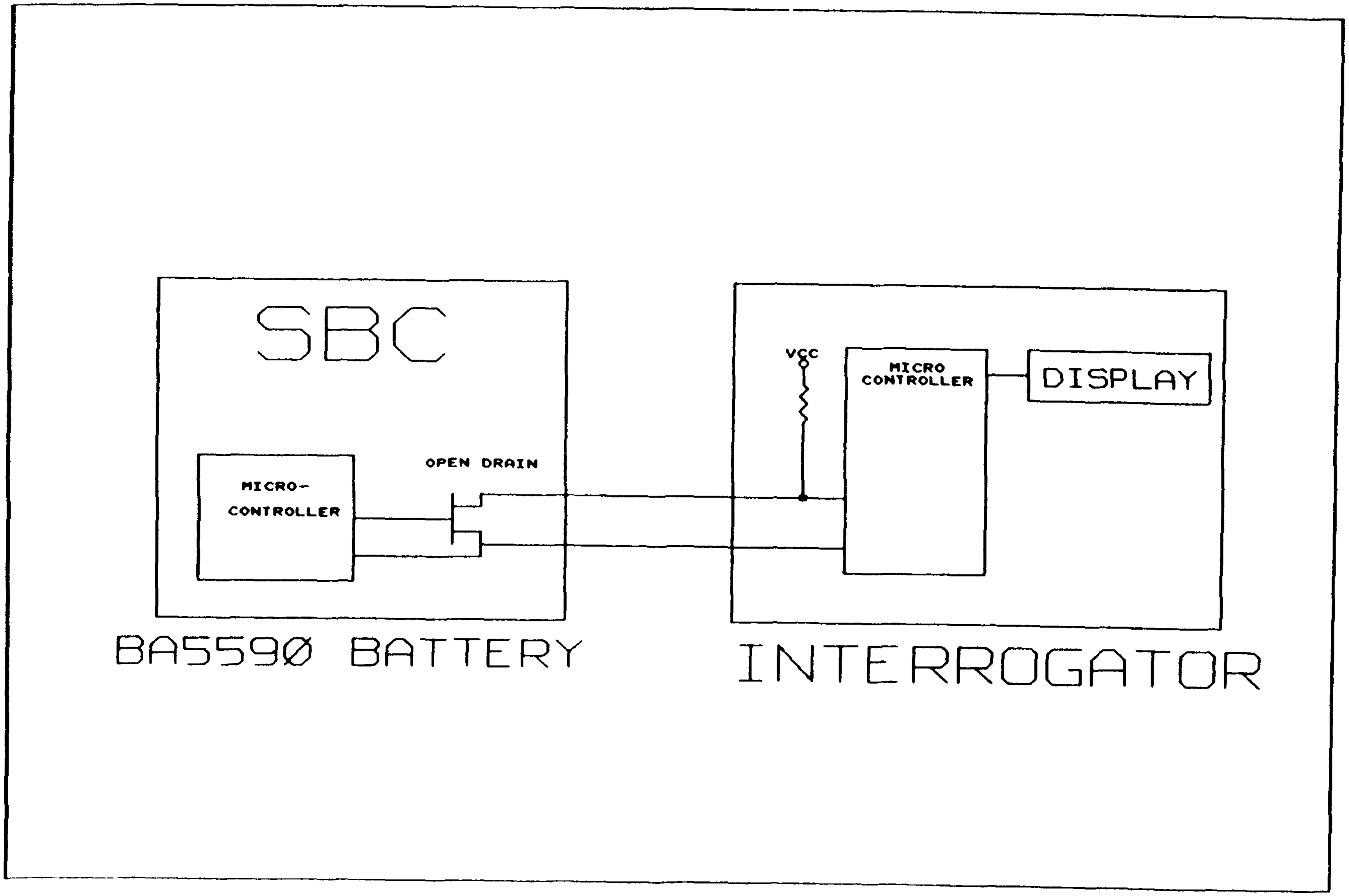

FIGURE 4. Block Diagram of 'Smart' Battery Interrogator

Microcontroller

An eight-bit microcontroller is used to receive the serial data from the battery, convert it from binary to BCD, and to control the display.

Display

Two seven-segment displays are used to display the remaining percentage of battery life. The range is 99 to 00.

THEORY OF OPERATION

The SBC tracks the ampere hour capacity remaining in the batteries by deducting the measured amount of capacity withdrawn from the initial (full) capacity value. The ratio of these numbers is used to calculate the remaining battery life. The SBC also detects a hazardous condition by scanning the battery cells. A hazardous condition exists if the voltage across any cell falls below 1.5 volts.

The current prototype hardware is designed to work with the BA-5590 battery, which can be utilized as either 10-series cells or as two parallel sets of five cells. Thus the SBC could be required to monitor either two 15V or one 30V system (nominal voltages). For these reasons, the SBC is designed to monitor battery systems under 15V. In the production of the BA-5590, two ASICs will be utilized and connected to each other, as discussed.

The processor, mixed-signal ASIC, and discrete devices comprising the SBC will be integrated into the battery enclosure, which will provide the user a means of determining the remaining energy in a battery, thus preventing premature disposal of the battery. The incorporation of the system will also provide a fail-safe operation of these high-powered lithium batteries.

SOFTWARE DESCRIPTION

Operational control of the SBC is maintained in a 2K assembly language program. Altogether, there are 42 modules, five of which are tables for various lookup algorithms. The control algorithm is oriented around servicing interrupts that are generated by the ASICs. An interrupt-service routine determines the source of the event and the type. It will call an appropriate routine, which will then shift serially the message broadcast from the ASIC. When the incoming event is completed by collecting the data, a flag bit is set in a central location, in memory, from which the main routine will poll and call various service routines, depending upon source of event and type.

A general timekeeping task runs in the background; time is controlled by the 68HC05 timer hardware, and is implemented by keeping track of one-second intervals. Various features require resolution of time to only one second; in some cases, they require delays of up to two minutes. Software also relies upon the timer subsystem to give accurate measurements of temperature. When this is in effect, the resolution is much greater and is a function of the microcontroller's crystal oscillator.

System Features

The SBC must control: the monitoring of the energy capacity of the battery packs; the monitoring of the cell voltages; the communication of the percentage remaining to the outside world; and the temperature and current integrator's measurements for known loads and temperatures for the purposes of calibrating the analog hardware.

Capacity (state of charge in energy units (EU))

Central to the operation of the software is a 380-byte lookup table that provides quantized values for capacity consumed for any given current load and battery temperature. The units for the EUs are defined in current time and can be related to an ampere-second or one coulomb. In order to simplify the design, operation, and applicability of the SBC, the capacity is normalized with respect to the integrating circuits utilized in the design. Thus, when the current monitor interrupts, it is always an indication that a defined number of EUs have been removed from the battery.

The actual EUs consumed when the integrating circuits interrupt comprise a function of both temperature and current load. When the battery is operated at high currents or low temperatures, it is inefficient; it consumes more capacity than the integrating circuits would indicate. Compensation is made by monitoring both temperature and current draw, and by using an adjustment factor that is determined from a two-dimensional lookup table. The values in the lookup table are normalized so that they may apply in other battery configurations.

Generation of the data within the table was performed by an error analysis of quantizing the domain of the temperature and current ranges into discrete steps. A least-squares approximation to battery characteristics was evaluated as a baseline against which discrete steps were evaluated until the error reached maximum tolerance. All values in the table are within five percent. Utilization of a larger lookup table or functional description would decrease the error imposed by the current approach.

The ASICs interrupt the hardware and shift a 16-bit count, which is a function of the amount of current flowing through the sense resistor. During the interrupt service routine, the 16-bit count is shifted into the microcontroller under software control.

The count 2 is inversely proportional to the amount of integrated current. To address the energy table, another table is searched, which relates to rows of the matrices to current elapsed times. An index in the range of 0-18 is found, which is used to address the rows of the energy table. When given a temperature index, the table can be addressed to find the variable amount of energy units.

In order to monitor battery capacity, a 24-bit running total of energy units is maintained for each ASIC. When the current integrator interrupts arrive and are serviced in the main loop, the running totals are decreased by the value looked up, plus 129 energy units. Over time, the remaining energy will pass through 64-percent (yellow status) and 32-percent (red status) categories; green indicates 100-65 percent.

Software also controls temperature measurement, which is accomplished by integrating the current through a thermistor that is attached near the battery casing. The temperature integrator will also ramp to a determined threshold voltage. The measurement of the duration of this ramp is performed by special hardware in the 68HC05, which allows it to measure time between external events.

Monitoring Cell Voltages

An ASIC will interrupt the processor and indicate which cell has fallen below 1.5 volts. Once the processor receives this data, it can shut down both sets of batteries. Requirements dictate that the determination to shut down must be activated by five consecutive samples where the cell or fuse has failed. If a cell exhibits a momentary loss in voltage due to a heavy current surge and then returns to safe levels, the counting of dropouts will be reinitialized.

A further requirement implemented in software is to avoid monitoring cell voltages when a battery pack has just been removed from the shelf. Before software begins counting hardware-detected low voltages, it must ensure that a minimum of continuous current of greater than 50 mA has been drawn from either group of cells for at least two minutes. This burns off an oxide that forms on the battery electrodes; during this time, internal cell resistance is higher than normal and sometimes yields voltages less than 1.5 volts.

Communications

The SBC gives an indication of the battery status by two methods. The most immediate method is to remove the battery pack from the equipment and depress an attached push-button switch. All three LEDs will light for four seconds to indicate nonmortality; then, either green, yellow, or red will light, also for four seconds, to indicate the lowest percentage of the cell groups. The percentages displayed are:

	Status	Color	Percentage Remaining
1.	Combat ready	green	100-65
2.	Training only	yellow	64-33
3.	End of Life	red	32-0

The second method of communication of status requires an auxiliary piece of equipment that has the capability to receive a serial message from the SBC. This method involves formatting the percentage of capacity remaining in the battery to a hexadecimal number ranging from 64 to 0, representing 100 to 0 percent and transmitting this data serially. This serial message is transmitted once per second; the serial format is one start bit and 8 data bits.

Transmitting the percentage in this manner also allows the user to determine more accurately the capacity remaining. When the battery has been shut down, either manually or by detecting the voltage threshold of a hazard, a fault code is transmitted on the serial output line. If monitoring equipment is available, the reason for shutdown can be determined as follows:

Code(Hex)		Reason
70	-	user has activated the shutdown scenario
71	-	battery group 1 - cell 1 failed
72	-	battery group 1 - cell 2 failed
73	-	battery group 1 - cell 3 failed
74	-	battery group 1 - cell 4 failed
75	-	battery group 1 - cell 5 failed
76	-	battery group 2 - cell 1 failed (most positive cell)
77	-	battery group 2 - cell 2 failed
78	-	battery group 2 - cell 3 failed
79	-	battery group 2 - cell 4 failed
7A	-	battery group 2 - cell 5 failed
7B	-	battery group 1 - fuse open
7C	-	battery group 2 - fuse failed

MANUAL BATTERY DISCHARGE ACTIVATION

Once the battery pack is removed from the equipment, the user is given the option of discharging the batteries if the capacity is less than 32 percent. When the button is depressed and released, the status of red will be displayed. The user is now given the option of discharging the battery by depressing the button again when the red LED is lit and holding it depressed for four seconds. A visual "handshake is given by software via the flashing red LED at a constant rate. Entry into the shutdown state is indicated by flashing all three LEDs. Shutdown discharges the battery, and once it is activated, there is no point of return. Releasing the push-button during the red LED flashing returns the system to normal operations.

Delay Operations

As mentioned previously, the SBC relies on several timers running concurrently. Some requirements are: to have a transmission of percentage remaining once a second; to have a guaranteed temperature measurement, which must be done every 2 seconds; to have a two-minute resettable period to allow oxides to be catalyzed; and to have various four-second intervals for displaying status in the LEDs.

Calibration

In order to avoid costly high tolerance parts and trimming pots, the SBC is designed to be calibrated by substitution of capacitors and laser trimming at the time of manufacture. The calibration routine is always executed after the board is powered. At this time, three temperature measurements are performed; after each one, the count that represents the elapsed time of the measurement will be transmitted, it then pauses. Capacitance must be substituted to force the measurement into the correct count for the particular temperature. Following the temperature measurements, software will loop for approximately 10 seconds while expecting a known load to be applied to the ASICs, one at a time. The counts represented the elapsed time of the current integration, which are now transmitted out serially. As before, capacitance and trimming must be done to bring the counts within specifications for the applied load. An approximate time of 12 seconds is spent within calibration; if it is not complete, the user has the option of resetting the SBC, and the process will repeat, or it will control transfers to normal operation.

CONCLUSION

A breadboard version of the SBC has been developed. This circuit has been fabricated, using discrete components, and tested for all of the above functions. Evaluation of this circuit has shown full compliance to the stated requirements.

The accuracy of the state of charge reading is ±5% overall and ±3% for operating conditions within the range of 0°C and 130°C.

Even though an ASIC-based model of the SBC has not been fabricated and tested, the breadboard prototype shows that an electronic battery controller can be developed and implemented. Also, since the controller is software driven there are various applications of the controller that have not been fully explored, such as incorporation of a smart electrical fuse and resettable thermal fuses.

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